

**A MECHANICAL REFRIGERATION SYSTEM
WITH A HIGH TURNDOWN RATIO**

This application claims the benefit of U.S. Provisional Application No. 60/474,516 filed May 30, 2003.

FIELD OF THE INVENTION

This invention relates to the design and operation of mechanical refrigeration systems to increase the effective operating range of the system.

BACKGROUND OF THE INVENTION

Electricity will play the major role in the growth of many areas of the world that are now considered underdeveloped, poor, or remote. Because many of these locations will never be serviced by large area electrical distribution systems, electricity is, or will be, provided on a local scale by various means. When supplying power to these small grids, the balancing of electrical supply and demand is critical to the distribution of high quality power. Quite often the source of electricity, such as diesel generators and renewable energy sources, has its own variability. Wind turbines, small hydroelectric devices, solar arrays, etc., all have electrical power outputs that vary with the available power input. For these electrical distribution systems, the ability to utilize the electrical energy at the same rate it is being generated is a useful property of any electrical load. When the electrical demand is larger than the supply, the grid suffers a brownout where the line voltage drops below its normal range. In the extreme, this condition may lead to damage or destruction of the generating system as it is overloaded beyond its design capacity. More likely, the generating system will detect the fault or overload and take steps to protect itself by tripping a circuit overload protection device. This, of course, leads to a blackout where electricity delivery to the grid has completely stopped.

Therefore, it is desirable for the electrical loads on the distribution system to be able to operate efficiently and perform useful work over a wide range of operation. As the overall electrical demand approaches that of the supply, it may be desirable to target individual loads for capacity reduction, specifically those loads where the average output,

rather than the instantaneous output, is of interest. These loads may be shut down completely or, in some cases, merely turned-down so that their work output decreases but more importantly their power consumption decreases. Given the ability to control the demand of the electrical grid, a power generation facility may increase the overall quality of the electrical energy being supplied to the end user.

The voltage and frequency variances inherent to many small grid systems complicate the suitability of individual loads to be turned down. Most motor loads are unable to operate over a wide range of operating voltages since they overheat if the voltage increases beyond nameplate rating and their power output decreases if operated below nameplate. Likewise, the ratio of the voltage to frequency must be within a very narrow window for the motor to operate efficiently and to provide useful work. Even while the operating voltage and frequency fall within acceptable limits, the process being driven may have limitations to the range of operation

Quite often, conditions are such that there is the capacity to generate electricity at a rate higher than it is being consumed. Normally this may be corrected by reducing the generator output or in rare instances by increasing a dump load whose purpose is to simply dissipate electrical energy while providing no useful work. If the electrical energy is being provided by a fuel powered device, such as diesel generator, then turning down the generating rate provides a decrease in fuel consumption and there is little wasted energy since the fuel may be stored indefinitely for later use. However, when the electrical energy is being provided by an alternate energy source having no fuel requirements, reducing the energy generation capacity is a wasted opportunity to provide surplus energy to either accomplish useful work or to be converted to a form suitable for storage and later use.

The concept of load leveling includes storage of surplus energy for a short period of time and reversion of the stored energy to useable work at a later time when there is less energy available. An example of loading leveling includes hydro storage where water behind a hydroelectric dam is pumped to a lake above the dam in the spring when there is a surplus of water, and that water is allowed to flow through the dam later in the year to turn the turbines. Another example is the regenerative fuel cells where electrical energy is used to electrolyze water into stored hydrogen and oxygen that is later used to

operate a fuel cell. A final example is a flywheel storage system where the electrical energy is converted to mechanical energy and vice-versa.

Another form of load leveling is to simply increase the production of a useful commodity while the energy is available so that the commodity does not have to be produced when the electrical energy is in limited supply or unavailable. An example would be the production of ice for those locations, such as fishing villages, where ice is required for the local economy. In that application load leveling is accomplished by making as much ice as possible while there is surplus energy so that the icemaker may be turned down or turned off when there is a shortage of energy. To continue the example, if the electrical energy is being provided by a renewable energy source, such as a wind turbine, any surplus ice that can be generated may be stored for later use when there is less energy available from the renewable energy source. However, a problem arises when the refrigeration capacity of a mechanical refrigeration system is varied beyond a narrow window, because the refrigeration capacity of a typical refrigeration system is adjusted for the purpose of controlling the temperature of the process, not for the purpose of limiting the amount of power being consumed.

There are four basic methods of capacity control employed in the industry. In a first method, if the refrigeration capacity is only slightly too large, then a portion of the hot gas exiting the compressor is shunted across the condenser and injected into the evaporator or liquid refrigerant line. Known as hot gas bypassing, this spoils the efficiency of the refrigeration cycle since the heat of compression is dumped into the cold reservoir (process/evaporator) rather than the hot reservoir (ambient/condenser). The second method of capacity control is very similar in that the amount of heat removed from the condenser is varied, e.g., in an air cooled condenser the fans are slowed to reduce the airflow through the condenser. As with hot gas bypassing the efficiency is spoiled since a portion of the heat of compression is left in the refrigerant when it enters the liquid evaporator. While these first two methods of capacity control decrease the effectiveness of the refrigeration cycle, they do not significantly change the power being consumed by the refrigeration system. Therefore, they are equivalent to operating a dump load where the surplus energy is simply wasted.

A third method of capacity control is available on systems having multi-cylinder compressors. In these systems, the intake valve of the compressor may be held open during both the intake and compression phases of the compression cycle, commonly referred to as unloading the compressor. When held open, the intake valve allows the refrigerant in the suction side of the compressor to enter the cylinder during the intake stroke and then exit the cylinder back into the suction piping system. Since the pressure of the refrigerant is unchanged, the compressor performs no work. Therefore, on compressors having an unloaded cylinder the work performed by the motor is reduced since the only work done by the unloaded cylinder is due to friction. As an example, a six cylinder compressor may have programmed stages where a specific system parameter is used to determine how many cylinders are compressing refrigerant and how many cylinders are unloaded.

Yet another method of capacity control is the cycling of the compressor. Generally reserved for when the capacity is much higher than the heat load, the compressor system will turn off when the target temperature is achieved and then return to operation when the upper limit is reached.

With the exception of cylinder unloading, these methods of capacity control work equally well with non-reciprocating forms of compressors, such as rotary lobe compressors, scroll compressors, etc., and have complementary capacity reduction techniques with absorption systems.

There are also less commonly used forms of capacity control such as rotational speed adjustment. However, returning to the example of ice making, reducing the capacity of the icemaker simply by slowing down the compressor and reducing the amount of refrigerant pumped through the cycle will result in a sharp decrease in the quality of ice.

Therefore, there is a need to control the refrigeration capacity of a vapor phase compression system in order to reduce the power demands of the refrigeration unit. It would be desirable to control or vary the refrigeration unit capacity without effecting the quality of the refrigeration.

SUMMARY OF THE INVENTION

The present invention provides a means of controlling the refrigeration capacity of a vapor phase compression machine, for the purpose of reducing the power demands of the refrigeration unit. The quantity of input power consumed by the refrigeration system may be controlled by an external means, such as a power distribution controller that adjusts the refrigeration system as a part of load balancing procedure. The operation and capacity of the refrigeration system may be adjusted by internal means, such as sensors on the compressor, motor, evaporator, condenser, target temperature, target capacity, etc.

To provide suitable turndown ratios, i.e., the ratio of maximum capacity to minimum capacity, the compressor speed and torque may each be varied to adjust and maintain the desired power delivery draw of the refrigeration system. This may be accomplished through any method of speed control such as variable speed controller and an inverter grade alternating current (AC) motor. With these systems infinite speed turndown ratios of the compressor are possible with turndown ratios of 1000:1 easily achieved. To further increase the turndown ratio, individual cylinders of the compressor may be partially or fully unloaded as the result of commands from the control system. Unloading cylinders allows the work being performed by the compressor to be reduced in an efficient manner, and therefore reducing the power requirements to maintain the compressor within a safe window of operation (e.g., minimum speed).

Optionally, the control system may allow the refrigeration system to control the speed of the process that is utilizing the refrigeration. As the real time capacity of the refrigeration system is determined, the amount of product that can be processed (e.g., food frozen, ice manufactured, etc.) can then be controlled so that the quality of the refrigeration process is maintained even as the capacity of the refrigeration process is reduced.

One method of controlling the heat input to the system includes maintaining the refrigeration evaporator in a flooded mode of operation and adjusting the refrigerant level within the evaporator to control the heat load delivered to the system. The effective surface area of the evaporator may be reduced by lowering the refrigerant level and thereby reducing the cold surface area in contact with the product or process.

In another aspect of the invention, the heat load is controlled through modification of the amount, location, or distribution of the heat load within or upon the system evaporator. For the specific example of the icemaker, the feed water distribution may be lowered or raised to adjust the portion of the evaporator in contact with the water.

Optionally, a low capacity method for operating the refrigeration system includes maintaining the velocity of refrigerant within the system piping and the turbulence inside the evaporator within acceptable ranges by continuously operating the compressor but delivering the refrigerant to the evaporator in small batches. Likewise, a means of increasing the flow rate of the low side of the refrigeration system is provided by providing periodic surges of gas flow from the evaporator to the compressor.

In another embodiment of the invention, the compressor is coupled to a wind turbine, either directly, through a transmission, or through a torque converter. In this system, the cylinder unloading method of capacity reduction may be used to reduce the power input requirements of the compressor for periods of light wind and to more closely match the low speed torque capabilities of the energy source.

In another embodiment of the invention, an absorption system may be utilized in place of the vapor phase compression system. In these systems the capacity control is the direct result of controlling the heat applied to the absorption system. Typically, absorption systems have an efficiency advantage over vapor phase compression when the energy input is in the form of heat rather than fuel or electricity.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the above recited features and advantages of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

Figure 1 shows refrigerant flow control of the effective surface area.

Figure 2 shows physical control of the effective surface area.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a means of controlling the refrigeration capacity of a vapor phase compression machine, for the purpose of reducing the power demands of the refrigeration unit. The quantity of input power consumed by the refrigeration system may be controlled by an external means, such as a power distribution controller that adjusts the refrigeration system as a part of a load balancing procedure. The operation and capacity of the refrigeration system may be adjusted by internal means, such as sensors on the compressor, motor, evaporator, condenser, target temperature, target capacity, etc. In another mode of operation, the power demands of the refrigeration system may be matched to the available power by monitoring the voltage, current, power factor and similar grid parameters. For example, the refrigeration system may include a controller to monitor the grid power at an appropriate place and then reduce the capacity of the refrigeration system to maintain the quality of the electrical grid, e.g., preventing brownouts, large power factors, etc.

Another aspect of the invention is the compressor speed and torque may each be varied to adjust and maintain the desired power delivery draw of the refrigeration system. This may be accomplished through any method of speed control including the use of conventional electrical power source coupled to a transmission or torque converter, direct current (DC) motor or alternating current (AC) motor and variable speed controller. The DC motor controller may be any type that is compatible with the grid and does not place an extreme amount of harmonics or other noise onto the power source. The variable speed AC controller may include open or closed loop vector control, constant volts/hertz, or any number of other methods for speed or torque control of AC motors. Infinite speed turndown ratios of the compressor are possible with turndown ratios of 1000:1 easily achieved.

To further increase the turndown ratio of the refrigeration system, the compressor may be fitted with a means of reducing the capacity by reducing the performance of the compressor system. One method of reducing the capacity of the compressor system is known as hot gas bypassing, where a controlled amount of hot refrigerant exiting the compressor is injected into the low pressure side of the refrigeration system, e.g., the evaporator. As a result of bypassing the condenser, where the heat of compression is

removed from the refrigerant, this hot gas spoils the efficiency of the system by boiling off a portion of the liquid refrigerant in the evaporator. The disadvantage of hot gas bypass, and other systems which merely spoil the efficiency of the refrigeration process, is that the amount of power consumed by the refrigeration system remains fairly constant, with only the refrigeration capacity reduced.

A preferred method of reducing the capacity of the compressor is to limit the rate at which gas is being compressed. This may be achieved by limiting the flow of gas into the compressor, limiting the compression ratio of the compressor, or by limiting the number of cylinders used for the compression cycle. A common method of reducing the number of cylinders actively compressing the refrigerant is to hold the intake valve open allowing refrigerant to be drawn into the cylinder from the low pressure suction line and then rejected back into the low pressure suction line. This effectively reduces or eliminates the gas throughput of that cylinder and is called "unloading" of the cylinder. Since there is little or no work being done on the refrigerant, the capacity of the compressor resulting from that cylinder is eliminated. Furthermore, since there is relatively little amount of power required to move the unloaded cylinder, the power consumption of the compressor is reduced along with the capacity. Since the amount of energy required to operate the compressor decreases with the capacity, this method of capacity reduction can be used to accurately control the power usage of the compressor. The present invention provides the ability to adjust the power demand of the refrigeration system by reducing the refrigeration capacity of the compressor, such as by unloading cylinders. Individual cylinders of the compressor may be partially or fully unloaded as the result of commands from the control system. Unloading cylinders allows the work being performed by the compressor to be reduced in an efficient manner, and therefore reducing the power requirements to maintain the compressor within a safe window of operation (e.g., minimum speed). Likewise, the individual cylinders may be returned to operation as energy becomes available, allowing the compressor to remain within desired operating parameters.

In some heat loads, such as comfort air conditioning or refrigerated storage, it is acceptable to have any rate of heat transferred between the cold and hot reservoirs since there are no short term demands for continuous operation. However, for those heat loads

where the refrigeration is being used to cool or freeze on demand, such as a food process line or ice maker, it is critical that the heat load does not exceed the capacity of the refrigeration equipment. Therefore, on systems where the capacity of the refrigeration equipment may possibly be varied on a continuous basis, the refrigeration control system may be given the ability to control the speed of the process that is utilizing the refrigeration. In this control system, a controller determines the present capacity of the refrigeration equipment by measuring the temperature (and/or pressure) of the evaporator system and the condenser system. Additional data, such as the refrigerant level in the high side liquid receiver, refrigerant level in the evaporator, compressor RPM, system power input, line voltage, line current, line phase factor, etc., may also be used to determine the real time capacity of the system. After the real time capacity of the system is determined, the amount of product that can be processed (e.g., food frozen, ice manufactured, etc.) can then be controlled.

A preferred refrigeration output control is as follows: The controller, or central control station, sets the desired amount of power to be consumed by the refrigeration system. The controller then limits the power (voltage and/or current) delivered to the motor and therefore the amount of power delivered to the compressor. The temperature of the cold reservoir (the evaporator making the ice) is then maintained even with reduced power input by reducing the flow rate of the water being delivered to the icemaker. This reduces the heat load of the evaporator allowing the evaporator temperature to be maintained. Alternately, the level of refrigerant in the evaporator, suction pressure, or discharge pressure may be used to maintain control of the water flow.

The evaporator may be operated in a flooded mode to allow the efficiency of the evaporator to be maintained across the entire range of refrigeration output. The liquid level of the refrigerant is then used to control the flow of refrigerant and to control the heat load (water to the icemaker).

In another optional aspect of the invention, a fixed- or variable-speed, supplemental oil pump, that is operated by a source other than the motor driving the compressor, is included in the system to ensure proper lubrication. The supplemental oil pump may be cycled off and on in response to one or more parameters such as oil pressure or compressor RPM.

Yet another optional aspect of the invention is the use of a low-pressure reservoir in communication with the suction side of the compressor. This reservoir may simply increase the volume of the low side reservoir so that short-term changes in the pumping capacity are damped. Alternatively, the reservoir may be valved into and out of the low-pressure side of the system to provide short-term load leveling, i.e., allowing the capacity of the compressor to be changed while allowing the short term pumping capacity upon the evaporator to remain stable. As the pumping capacity of the compressor is increased, due to an increase in the available power, a portion of the excess pumping capacity is used to evacuate the reservoir in preparation for the next short-term reduction in pumping capacity. This may be accomplished by an additional compressor, or more preferably, by alternately pumping on the reservoir and the evaporator such that the temperature of the evaporator is maintained while the pressure of the reservoir is taken significantly below that of the evaporator and more preferably to a partial vacuum.

An optional aspect of the control system is the ability of the refrigeration system to control the speed of the process that is utilizing the refrigeration. To determine the real time capacity for heat transfer, probes are provided so that the controller is able to measure the temperatures (and/or pressures) of the evaporator system and of the condenser system. Additional data, such as the level of refrigerant in the high side liquid receiver, refrigeration level in the evaporator, compressor RPM, system power input, line voltage, line current, line phase factor, etc., may also be used to determine the real time capacity of the system. After the real time capacity of the system is determined, the amount of product that can be processed (e.g., food frozen, ice manufactured, etc.) can then be controlled so that the quality of the refrigeration process is maintained even as the capacity of the refrigeration process is reduced. Likewise, as additional energy becomes available the capacity of the refrigeration process may be increased followed by an increase in the rate of product handling or generation. The system controller may be set for the maximum amount of ice produced, the maximum amount of power consumed, the minimum incoming line voltage to be maintained, or may be used to even out the loads in the individual phases of the incoming power lines or to remove harmonics.

A specific example of the above feature of the control system is using the refrigeration system to produce ice, where the final temperature of the ice must be

maintained to produce high quality ice. In typical icemaker systems, water is placed in contact with a cold surface to freeze the water into ice. In each icemaker system the placement or quantity of water (load) may be modified to more closely match the load to the refrigeration capacity. In the simplest case of a block ice machine, the rate at which the ice cans are cycled defines the overall heat load. In the case of the tube chunk machines and cube machines, the number of active surfaces (tubes, pans, etc.) and the flow rate of feed water may be adjusted to maintain the evaporator temperature(s) of the system. In spinning disk flake machines the water level in the reservoir containing the disk may be raised or lowered so that varying amounts of the disk are coated with water. Finally, in the example of the drum and scraper (or auger) flake machines, modifying the feed water flow rate as well as the surface area of the drum being utilized will allow the production to be closely matched to the capacity.

A similar example is using the refrigeration system to refrigerate, dehumidify, or otherwise process air and the flow rate of air across the evaporator may be adjusted to maintain a fixed air temperature on the discharge side of the evaporator.

In another aspect of the system, the refrigeration evaporator is maintained in a flooded mode of operation and adjustments to the refrigerant level within the evaporator are used to control the heat load delivered to the system. The heat load is modified since the substantial portion of the heat is removed from the area of the evaporator located below the top liquid level of the refrigerant. Lowering the refrigerant level and thereby reducing the cold surface area in contact with the product or process reduces the effective size (i.e., height) of the evaporator. In the specific example of a tube or barrel type icemaker, the feed water in contact with the evaporator surface located above the level of the liquid refrigerant will only marginally be cooled. Only when the water approaches the height corresponding to the top surface of the refrigerant within the evaporator will heat be removed from the feed water. If the refrigeration capacity is reduced to some fraction of full output, lowering the refrigerant liquid level to approximately the same fraction of the full level effectively eliminates the upper portion of the icemaker that is above the refrigerant level liquid.

In another aspect of the invention, the placement and number of water sources or nozzles to the evaporator for the production of ice may be varied. The positioning of the

initial point of introduction of the water on the surface of the evaporator may be varied on a real time basis or any other suitable basis to increase or decrease the heat load upon the evaporator. As examples, the height of the water source or nozzle above the base of the evaporator surface may be increased to increase the heat load and the height of the water source lowered to reduce the heat load. Likewise, the utilized surface area of the evaporator may be adjusted in terms of its width or angular portion of a circular evaporator by adjusting the placement or number of water sources across the top surface. Furthermore, it is possible to reduce the heat load of the evaporator more rapidly than simply adjusting the internal liquid-level of the refrigerant, by reducing, redirecting or stopping the water flow to one or more portions of the evaporator.

In another embodiment of the controlled level mode of operation, the temperature of the liquid refrigerant within the evaporator is maintained at a preset value to control the quality of the process (e.g., ice manufacturing). As the temperature of the evaporator changes, the amount of refrigerant entering the evaporator is adjusted such that an increasing evaporator temperature leads to a reduction of incoming refrigerant. Continued pumping on the evaporator (withdrawing vaporized refrigerant) with a reduced refrigerant liquid flow into the evaporator will result in the lowering of the refrigerant level and therefore reductions in the active area of the evaporator and the heat load. Since the temperature of the refrigerant in a two-phase evaporator is well characterized in terms of the pressure of the evaporator, the pressure of the evaporator may be used as the controlling parameter. Furthermore, a pressure-operated valve controlling the introduction of liquid refrigerant to the evaporator may be used to eliminate the need for an electronic or other control system.

Another benefit of adjusting the liquid refrigerant level in the evaporator is the capability provided to the system to maintain the turbulence within the evaporator to keep the refrigeration oil entrained in the refrigerant. Under full heat load conditions, the refrigerant is continuously undergoing vigorous boiling as the incoming heat vaporizes the liquid refrigerant over the entire surface of the evaporator. However, during high turndown modes of operation, the boiling per unit area of evaporator reduces as the heat load reduces and the boil becomes less vigorous, creating the potential for the refrigerant oil to separate and remain near the surface of the liquid. A benefit of adjusting the level

of the liquid refrigerant is to maintain the heat transfer per unit area of the evaporator (effective area) at a value that results in a sufficiently rapid boil of the refrigerant.

In a related optional aspect of the invention, during a low capacity mode of operation the velocity of refrigerant within the system piping and turbulence within the evaporator may be maintained within acceptable values by operating the compressor continuously but delivering the refrigerant to the evaporator in small batches. The addition or increase in capacity of a low side accumulator will assist in providing a larger volume for the low-pressure gas. In this mode of operation the refrigerant flow to the evaporator is controlled or periodically stopped to allow an increased pressure difference between the high side liquid reservoir (receiver) and the low side reservoir (evaporator and accumulator). When the liquid refrigerant valve is reopened, the flow rate of refrigerant will reach higher peaks than its average value. In a similar manner, a valve placed between the evaporator and low side accumulator will allow a pressure differential to be generated between those two low-pressure reservoirs with the accumulator acting as a vacuum source. As with the high side liquid, periodically closing and reopening this valve will temporarily increase the velocity of the gas in the low side of the system, flushing trapped refrigerant and oils from the piping.

As another optional aspect of the invention related to adjusting the level of liquid refrigerant in the evaporator, the evaporator may be provided with a floating oil skimmer to provide removal of refrigeration oil that forms on the surface of many refrigerants. Alternatively, the evaporator may be fitted with multiple taps at different heights to remove the oil film. Each tap may be provided with a valve so that only the tap level with the top surface of the liquid refrigerant is utilized. Another embodiment would consist of a tube that may be adjusted by an external means to track the top surface of the refrigerant. Finally, the system may be fitted with a mechanical or refrigerant driven mixer, or designed and operated in such a manner that there is sufficient turbulence to maintain the oil in solution, allowing oil to be more easily removed with less concern for the location of the liquid level. In the latter embodiment, the oil would remain entrained in the refrigerant and would be carried away with a controlled amount of liquid refrigerant from a fixed port that is not necessarily near the top surface. In any of these embodiments where a portion of the liquid is being drawn from the evaporator, this liquid

refrigerant/oil mixture may be expanded in a heat exchanger and the energy utilized in another portion of the refrigeration cycle before returning the vaporized refrigerant and oil to the compressor. Conversely, for operation with refrigerants that are lighter than oil (such as ammonia) the oil may simply be withdrawn from the bottom of the evaporator sub-system.

A common method of maintaining circulation within flooded evaporator systems, such as a barrel type ice maker, is to place a baffle within the evaporator with the first side of the baffle facing the heat source and the second side of the baffle facing away from the heat source. An open area above and below the liquid level of the refrigerant allows natural circulation due to the rising refrigerant bubbles near the heat source to keep the refrigeration oil entrained in the refrigerant. However, this method of creating natural circulation cannot be utilized when the level of the refrigerant is varied and more specifically when the top level of the refrigerant is lowered below the top of the baffle. Therefore, another optional aspect of the invention is a baffle arrangement that provides natural circulation regardless of the level of the refrigerant in the evaporator. Replacing the solid baffle with a baffle that is perforated, louvered, or is otherwise substantially open will allow circulation upward with the bubbles near the heat source and liquid flow downward on the second side of the baffle, away from the heat source. In another embodiment, replacing the baffle with chevrons, or another means of redirecting the bubbles to columns, will provide 'chimneys' where the rising bubbles draw the refrigerant upwards and areas with fewer bubbles where the liquid refrigerant will more easily downflow. Spacing of these chimneys around the circumference of the evaporator will provide circulation of the refrigerant and oil independent from the liquid level of the refrigerant.

In another aspect of the invention, following a significant reduction in the available power to the compressor, a portion of the liquid refrigerant in the evaporator may be rapidly removed from the evaporator and evaporated in a separate heat exchanger such that the heat taken up by the evaporation is provided by the high pressure liquid in a high-side liquid storage reservoir. Therefore, the liquid level in the primary evaporator, (the evaporator connected to the process) may be quickly lowered to reduce the heat load to the primary evaporator. The heat uptake capacity of the excess refrigerant will then be

utilized to sub-cool the liquid refrigerant feeding the evaporator, and therefore reduce the enthalpy (heat content) of the high-pressure liquid refrigerant. In effect, this method of load leveling utilizes a short-term surplus of liquid refrigerant in the process evaporator to reduce the temperature of the refrigerant available to enter the process evaporator (and therefore making that refrigerant more effective in cooling the evaporator when the refrigerant is later released into the evaporator). Further, the liquid refrigerant may be evaporated into a low-pressure reservoir so that the load on the compressor is not increased. Vapor refrigerant may then be removed from the low-pressure reservoir during periods of higher pumping capacity. Conversely, during short term periods of excess refrigeration capacity, a portion of the liquid refrigerant in the high-pressure reservoir or liquid refrigerant from the process evaporator may be used (i.e., evaporated in a heat exchanger and the vapor returned to the compressor) to sub-cool the remaining liquid refrigerant in the high-pressure reservoir.

Optionally, the overall efficiency of the unit may be established, displayed, and/or transferred to a control station, or used within the software control strategy to modify the operating parameters. For example, as less energy becomes available and the refrigeration capacity is reduced, (the overall efficiency of the system will decrease due to ancillary loads, e.g., control system, pumps, fans, etc.) it may be more desirable to stop the refrigeration process and utilize the energy somewhere else on the grid.

In another embodiment of the invention, the compressor is coupled to an alternate energy source that produces rotational motion (e.g., wind turbine or water turbine), either directly, through a transmission, or through a torque converter. In this type of system, the cylinder unloading method of capacity reduction may be used to reduce the power input requirements of the compressor for periods of light wind. Since many alternate and renewable energy sources, such as wind turbines, have poor starting torque characteristics, cylinders may be unloaded, to minimize the starting torque requirements of the compressor so that they more closely match the low speed torque capabilities of the energy source.

In another embodiment of the invention, an absorption system may be utilized in place of, or in conjunction with the vapor phase compression system. In these systems the capacity control is the direct result of controlling the heat applied to the absorption

system. Typically, absorption systems have an efficiency advantage over vapor phase compression when the energy input is in the form of heat rather than fuel or electricity.

Example

An apparatus having a mechanical vapor phase compressor, condenser, flooded evaporator, and control system was designed having a maximum capacity of 5 tons of ice per day delivered at -10°F with a condenser temperature of 105°F and freshwater input at a temperature of 65°F . The system included a variable speed motor controller capable of operating a 15 horsepower inverter grade motor across a speed range from zero to 1800 RPM. This motor was directly coupled to a four cylinder, open frame compressor (Carrier Model 5F40), fitted with individual cylinder unloaders, auxiliary oil cooler, water cooled heads, and suction and discharge service valves. The system was operated on R-22. Hot refrigerant gas exited the compressor and was condensed in a water cooled shell and tube condenser having a capacity of approximately 8-tons. The condensed refrigerant was then held in a liquid receiver having a capacity of 80 pounds of refrigerant. Using a solenoid valve refrigerant was delivered to the evaporator system. The refrigerant liquid level was controlled by an evaporator pressure controlled expansion valve. Liquid refrigerant and refrigeration oil was recovered from the evaporator and vaporized in a low temperature heat exchanger with heat being provided by the liquid refrigerant being delivered to the evaporator. This liquid refrigerant/oil recovery line was provided with a solenoid valve that was closed when the temperature of the refrigerant exiting the low temperature heat exchanger was below a predetermined value. This may occur when the compressor is operating at low capacity, when there is not sufficient heat load to draw liquid refrigerant into the evaporator, or when the control system has adjusted other parameters of the system so that the capacity of the system is reduced. This refrigerant/oil recovery valve also closed when the compressor was cycled off to prevent liquid refrigerant from entering the low-pressure accumulator.

A barrel type evaporator served as the primary evaporator and cold reservoir heat exchanger for the system. The level of refrigerant within the evaporator was raised or lowered to effectively change the size (height) of the evaporator and therefore adjust the amount of chilled surface area available for generating ice. The system parameters were

adjusted such that the temperature of the liquid within the evaporator was maintained at approximately -15° F.

Ice was generated on the surface of the evaporator and removed by a mechanical scraper. The thickness of ice is controlled by adjusting the rate at which the scraper harvests the ice. The rate of ice generation is controlled by both the liquid refrigerant within the evaporator as well as the fraction of the drum over which water is applied. The drum may be divided into four portions. The first portion is the fraction of the circumference of the drum over which water is delivered or poured over the drum. The water delivery pumping rate and solenoid valve are controlled so that water is only delivered to a well defined portion of the drum. The second portion of the drum is where the water that has become ice is allowed to sub-cool to the desired temperature, related to both the rate of ice making and the temperature of the liquid refrigerant within the drum. The third portion of the drum is where the harvesting scraper is removing the ice from the surface and delivering the ice to the output hopper. The fourth portion of the drum is the fraction of the drum that is left unused to match the heat load to the capacity of the compressor. The speed of rotation of the harvester is monitored and adjusted by the control system. The water delivery nozzle preferably rotates with the harvester with the angle between the nozzle and harvester adjustable by the user.

Vapor phase refrigerant is removed from the top of the evaporator and travels through a low side accumulator before being returned to the compressor. A solenoid valve between the evaporator and accumulator allows a pressure differential to be generated and dumped, causing surges of vapor refrigerant in the piping system. This surge mode is utilized during extremely low capacity operation to prevent oil accumulation in the piping.

While the foregoing is directed to the preferred embodiment of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims which follow.